

Lower limits on R -parity-violating couplings in supersymmetry

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Abstract

We interpret the results of searches for strongly interacting massive particles to place absolute lower limits on R -parity-violating couplings for squarks with mass below 100 GeV. Recent searches for anomalous isotopes require that there be a baryon-number-violating or lepton-number-violating coupling larger than 10^{-20} – 10^{-19} . Using recent data from searches for stable particles at the CERN Large Electron Positron collider (LEP) we demonstrate that this lower limit increases by 12 orders of magnitude, to an R -parity-violating coupling larger than 10^{-8} – 10^{-7} for squarks of mass less than 90 GeV. In the presence of an R -parity-violating coupling of this magnitude, neutralinos cannot explain the dark matter density in the Universe.

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I. INTRODUCTION

In supersymmetric extensions of the standard model of elementary particle physics, particles are typically assigned a new quantum number called R parity (R_p) [1]. Particles of the standard model are defined to have even R_p , and their corresponding superpartners have odd R_p . If R parity is conserved, then superpartners must be produced in pairs, each of which decays to a final state that includes at least one stable lightest supersymmetric particle (LSP). One appealing feature of R -parity conservation is that if the LSP is a neutralino, then it is naturally predicted to exist with the necessary relic density to explain the dark matter density in the Universe [2].

In contrast, if R parity is not conserved, then supersymmetric particles may decay into standard model particles, and supersymmetry may not provide an explanation of dark matter. Further, many of the postulated signatures of supersymmetry (SUSY), such as missing energy in high energy collider experiments, may not exist. In particular, many of the exclusion limits on squark masses may no longer apply if R parity is violated. On the other hand, if the R -parity-violating couplings are small enough, then superparticles may appear to be stable on a time-scale relevant for collider searches. In the search for physics beyond the standard model in cosmological and terrestrial experiments, it is of substantial importance to address explicitly the question of R -parity violation, a possibility that we explore in this Letter.

The present *upper* bounds on possible R -parity-violating couplings are obtained principally from next-to-leading order quantum corrections to the rates for particle decays and neutral meson mixing. These bounds are relatively restrictive for the first generation of quarks and leptons but are much less so for states of the second and third generations [3]. In this Letter, we approach R -parity-violating couplings from the other direction. We demonstrate that there must be strong *lower* bounds on R -parity-violating couplings for a large range of squark masses. Otherwise, squarks with mass in these ranges cannot exist.

We focus on squarks with mass below 100 GeV. Although it is widely held that squarks in this range are ruled out by experiment, this limitation does not apply in general SUSY-breaking scenarios if the states with lowest mass are coupled feebly to the neutral gauge boson Z . A scenario with a light bottom squark \tilde{b} along with a gluino of moderate mass is proposed in Ref. [4]. This model provides an explanation for the large excess in the

b -quark cross section measured at hadron colliders [5, 6], and is supported by the recent observation of a large time-averaged $B^0\bar{B}^0$ mixing probability $\bar{\chi}$ [7]. If the lighter of the two bottom squarks is an appropriate mixture of left-handed and right-handed squarks, its tree-level coupling to the Z can be arbitrarily small, permitting good agreement with the precise measurements of Z -peak observables [8], including effects at loop-level [9]. Data from searches for massive stable particles produced at the CERN Large Electron Positron collider (LEP) require that, if it exists, the lighter of the two \tilde{b} 's cannot live longer than about 1 nanosecond [10], meaning that R parity is broken.

In Sec. II, we establish our notation and provide expressions for the partial widths for squark decay into various final states. These partial widths are proportional to the square of the R -parity-violating couplings. In Sec. III we demonstrate that a lower bound on baryon-number or lepton-number violating couplings of 10^{-20} can be extracted from primordial abundance searches. Then, using data from searches for massive stable particles produced at LEP, we place absolute lower bounds on R -parity-violating couplings as a function of squark mass. For squarks with mass less than 90 GeV, we show that the lower bounds on baryon-number or lepton-number violating couplings improve to 10^{-8} – 10^{-7} . Conclusions and implications are addressed in Sec. IV.

II. SUPERSYMMETRIC NOTATION

There are several popular choices of convention for the squark mixing angles and for the normalization of R -parity-violating couplings. For evaluating the lifetimes of squarks, we use the R -parity-violating superpotential [11]

$$W_{\mathcal{R}_p} = \epsilon^{\sigma\rho} \lambda'_{ijk} L_{i\sigma} Q_{j\rho}^\alpha D_{k\alpha}^c + \epsilon^{\alpha\beta\gamma} \lambda''_{ijk} U_{i\alpha}^c D_{j\beta}^c D_{k\gamma}^c, \quad (1)$$

where (σ, ρ) are $SU(2)$ indices, (α, β, γ) are $SU(3)$ color indices, and (i, j, k) are generation indices. L and Q are leptonic and hadronic left-handed superdoublets, respectively. U^c and D^c are right-handed up- and down-type conjugate superfields, respectively. The first term violates lepton number, and the second term violates baryon number. The dimensionless coupling strengths λ'_{ijk} and λ''_{ijk} measure the strength of lepton-number and baryon-number violation, respectively. In general the couplings are complex.

The physical squarks are a mixture of the scalar partners of the left- and right-chiral

quarks. The mass eigenstates are two complex scalars, \tilde{q}_1 and \tilde{q}_2 , expressed in terms of left-handed (L) and right-handed (R) squarks, \tilde{q}_L and \tilde{q}_R . We choose the squark mixing matrix such that \tilde{q}_1 is mostly right-handed when the mixing angle is small.¹

$$\begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \end{pmatrix} = \begin{pmatrix} \cos \theta_{\tilde{q}} & \sin \theta_{\tilde{q}} \\ -\sin \theta_{\tilde{q}} & \cos \theta_{\tilde{q}} \end{pmatrix} \begin{pmatrix} \tilde{q}_R \\ \tilde{q}_L \end{pmatrix}. \quad (2)$$

Given the mixing matrix above, the partial widths of a squark decaying into two massless quarks are [12]

$$\begin{aligned} \Gamma(\tilde{q}_1 \rightarrow qq) &= \frac{m_{\tilde{q}_1}}{2\pi} \cos^2 \theta_{\tilde{q}} |\lambda''_{ijk}|^2, \\ \Gamma(\tilde{q}_2 \rightarrow qq) &= \frac{m_{\tilde{q}_2}}{2\pi} \sin^2 \theta_{\tilde{q}} |\lambda''_{ijk}|^2, \quad j < k. \end{aligned} \quad (3)$$

The partial widths of an up-type squark that decays into a massless quark and lepton are

$$\begin{aligned} \Gamma(\tilde{u}_{1j} \rightarrow \bar{e}_i d_k) &= \frac{m_{\tilde{u}_{1j}}}{16\pi} \sin^2 \theta_{\tilde{u}_j} |\lambda'_{ijk}|^2, \\ \Gamma(\tilde{u}_{2j} \rightarrow \bar{e}_i d_k) &= \frac{m_{\tilde{u}_{2j}}}{16\pi} \cos^2 \theta_{\tilde{u}_j} |\lambda'_{ijk}|^2, \end{aligned} \quad (4)$$

and for a down-type squark, they are

$$\begin{aligned} \Gamma(\tilde{d}_{1j} \rightarrow \bar{\nu}_i d_k) &= \frac{m_{\tilde{d}_{1j}}}{16\pi} \sin^2 \theta_{\tilde{d}_j} |\lambda'_{ijk}|^2, \\ \Gamma(\tilde{d}_{2j} \rightarrow \bar{\nu}_i d_k) &= \frac{m_{\tilde{d}_{2j}}}{16\pi} \cos^2 \theta_{\tilde{d}_j} |\lambda'_{ijk}|^2, \end{aligned} \quad (5)$$

$$\begin{aligned} \Gamma(\tilde{d}_{1k} \rightarrow \nu_i d_j) &= \frac{m_{\tilde{d}_{1k}}}{16\pi} \cos^2 \theta_{\tilde{d}_k} |\lambda'_{ijk}|^2, \\ \Gamma(\tilde{d}_{2k} \rightarrow \nu_i d_j) &= \frac{m_{\tilde{d}_{2k}}}{16\pi} \sin^2 \theta_{\tilde{d}_k} |\lambda'_{ijk}|^2, \end{aligned} \quad (6)$$

$$\begin{aligned} \Gamma(\tilde{d}_{1k} \rightarrow e_i u_j) &= \frac{m_{\tilde{d}_{1k}}}{16\pi} \cos^2 \theta_{\tilde{d}_k} |\lambda'_{ijk}|^2, \\ \Gamma(\tilde{d}_{2k} \rightarrow e_i u_j) &= \frac{m_{\tilde{d}_{2k}}}{16\pi} \sin^2 \theta_{\tilde{d}_k} |\lambda'_{ijk}|^2. \end{aligned} \quad (7)$$

If one R -parity-violating coupling is large compared to the others, then only one of these partial widths will be applicable at any given time. For simplicity we present results assuming one significant coupling. Any other combination of couplings may be derived using the widths above.

¹ Note we use a different mixing convention here than presented in Ref. [12].

III. A SMALLEST R -PARITY-VIOLATING COUPLING

A. Limits on squark masses and R -parity-conserving couplings

To place R -parity-violating couplings into context, we begin with a brief summary of the current limits on R -parity-conserving decays of squarks. In R -parity-conserving SUSY, squarks are either completely stable, or undergo R -parity-conserving decays into final states containing a stable sparticle. If the daughter sparticle is neutral, then there will be missing energy in the event. Many limits on squark masses are based on searches for jets plus missing energy, and some are predicated on the assumption that couplings to the Z boson are not suppressed. In our work, by contrast, we wish to place the most conservative lower limits on R -parity-violating couplings, and we therefore include cases in which the squarks decouple from the Z boson.

In the absence of strong coupling to the Z boson, direct limits on the existence of up-type and down-type squarks differ significantly. Because of their larger coupling to photons, the R -parity-conserving decay of up-type squarks to any lightest supersymmetric particle (LSP) is ruled out for $m_{\tilde{q}} < 63$ GeV [10, 13, 14, 15]. This limit increases to 83–89 GeV in any case where $\Delta m = m_{\tilde{q}} - m_{\text{LSP}} > 5$ GeV [15, 16]. Down-type squarks with masses between 40–89 GeV, R -parity-conserving decays, and $\Delta m > 5$ GeV are also excluded. However, below 40 GeV the only limits on R -parity-conserving decays for down-type squarks come from exclusions of possible decay products. All sleptons, charginos and neutralinos are excluded below 37 GeV [13], and stable gluinos are excluded below 27 GeV [10]. Unless there is a stable gluino between 27–35 GeV or finely-tuned LSP mass, all squarks less than 83–89 GeV will either appear to be stable on the time-scale of accelerator experiments, or decay via R -parity-violating interactions. For the rest of this Letter, we will consider the R -parity-conserving decays to be excluded.

B. R -parity-violating couplings

Limits on the relic abundances of stable primordial particles may be used to set an initial lower bound on R -parity-violating couplings. For hadron masses less than 100 GeV, Fermi motion in nuclei is expected to prevent the capture of exotic states in the nuclei of light elements, such as sodium or oxygen. Heavy elements, such as gold and iron, are believed to

be capable of capturing the strongly interacting massive particles (SIMPs) [17]. Recently, a search for anomalous gold and iron isotopes was used to set limits on the cosmological density parameter Ω_S , the ratio of the density of relic primordial SIMPs to the critical density. Upper limits of $\Omega_S < 10^{-6}$ to 10^{-4} were extracted for the mass range 2.8 to 100 GeV [18]. If the assumptions regarding exposure times for the samples and capture cross sections are correct, then completely stable primordial squarks may be excluded below 100 GeV. These bounds can be evaded, however, if the primordial squark density has decayed to roughly 1/10 of its predicted abundance. As discussed in Sec. III A, R -parity-conserving decays are excluded for squarks of mass less than 100 GeV. Therefore the primordial abundance limit implies that there must be at least one R -parity-violating coupling greater than $10^{-20}/\sqrt{m_{\tilde{q}}[\text{GeV}]}$. In the case of mixing, this limit may be larger by $|1/\sin\theta_{\tilde{q}}|$ or $|1/\cos\theta_{\tilde{q}}|$.

While a few combinations of masses and R -parity-violating couplings have been excluded,² we now show that there is a strong lower limit on at least one baryon-number or lepton-number violating coupling for all squarks of mass less than 85–90 GeV by using the results of a new ALEPH study [10, 20]. From the absence of heavy hadron tracks and unexplained missing energy, the ALEPH study concludes that squarks, if produced, decay before leaving a discernible signature. That investigation rules out squarks that live more than a few nanoseconds between the electroweak precision lower limit of 1.3 GeV and 92 (95) GeV for down-type (up-type) squarks [10, 20]. Working from the results of that paper, we use our Eqs. 3–7 to derive the minimal necessary R -parity-violating couplings under the assumption of only one non-zero coupling.

We present our results in Figs. 1 and 2. The curves in Fig. 1 show that there must be a baryon-number-violating coupling λ'' larger than $\sim 5 \times 10^{-9}$ – 10^{-7} for squark masses less than 90 GeV. If there are no large baryon-number-violating couplings, then the curves in Fig. 2 show that there must be a lepton-number-violating coupling λ' larger than $\sim 10^{-8}$ – 5×10^{-7} for squark masses less than 90 GeV. In these figures, we distinguish the minimal couplings obtained in the cases where the lightest squarks (\tilde{d}_1 or \tilde{u}_1) decouple from the Z -boson ($\sin\theta_{\tilde{d}} \approx 0.39$ or $\sin\theta_{\tilde{u}} \approx 0.56$). The decrease with mass of the lower limits in part reflects the fact that partial widths in Eqs. 3–7 are proportional to the squark mass.

² For example, bottom squarks of mass between 3.5 and 4.5 GeV decaying through λ'_{i23} are ruled out by the CLEO Collaboration [19].

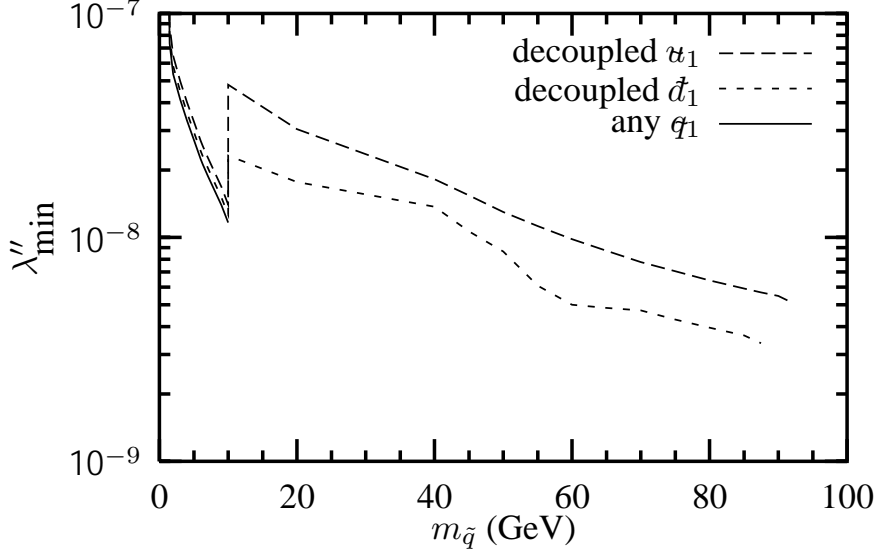


FIG. 1: Lower limits on the baryon-number-violating couplings λ'' as a function of squark \tilde{q}_1 mass. The solid line ($m_{\tilde{q}} < 10$ GeV) indicates an absolute lower limit on the couplings. The dashed lines indicate the limits where \tilde{d}_1 or \tilde{u}_1 decouple from the Z -boson ($\sin \theta_{\tilde{d}} \approx 0.39$ or $\sin \theta_{\tilde{u}} \approx 0.56$). For $m_{\tilde{q}} > 10$ GeV the dashed lines are also absolute lower limits.

There are two distinct regions in Figs. 1 and 2. In the region of small squark masses, the assumed production process is $e^+e^- \rightarrow q\bar{q}g$, with $g \rightarrow \tilde{q}\tilde{q}^*$. Beyond a squark mass of roughly 10 GeV, there are not enough events to provide a competitive limit. In the higher mass region the assumed production process is $\tilde{q}\tilde{q}^*$ pair production, and a lifetime limit of about 1 ns can be set up to 92 GeV. Below a squark mass of 10 GeV the relevant production process is independent of mixing angle. Therefore, the lower bound for a given squark mixing-angle is $|1/\sin \theta_{\tilde{q}}|$ or $|1/\cos \theta_{\tilde{q}}|$ larger than the absolute bound. Above 10 GeV the cross section for pair-production is measured under the assumption that the squarks are decoupled from the Z boson. If the mixing angle changes, then the squarks couple to the Z -boson and the cross section used to estimate the lifetime increases dramatically. The mixing-angle dependence will temper or enhance the large increase in the lower bound in a experiment-dependent manner that we do not attempt to estimate.

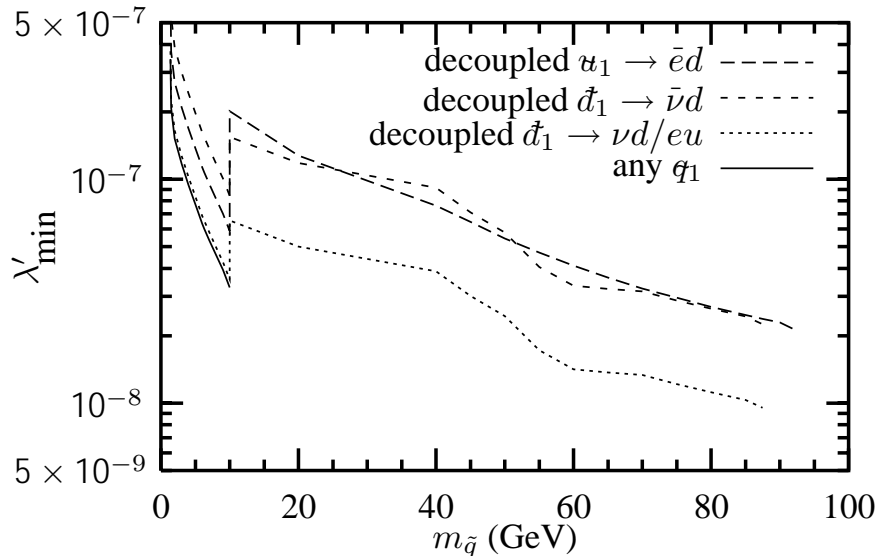


FIG. 2: Lower limits on the lepton-number violating couplings λ' as a function of squark mass. The solid line ($m_{\tilde{q}} < 10$ GeV) indicates an absolute lower limit on the couplings. The dashed lines indicate the limits where \tilde{d}_1 or \tilde{u}_1 decouple from the Z -boson ($\sin \theta_{\tilde{d}} \approx 0.39$ or $\sin \theta_{\tilde{u}} \approx 0.56$), and are listed by decay. For $m_{\tilde{q}} > 10$ GeV the dashed lines are also absolute lower limits.

IV. CONCLUSIONS

If there are squarks with mass less than about 90 GeV, both exotic isotope searches and data from LEP require that they are not stable. Since R -parity-conserving decay modes are explicitly excluded, exotic isotope searches imply that R -parity-violating couplings greater than $10^{-20}/\sqrt{m_{\tilde{q}}[\text{GeV}]}$ must be present if there are squarks of mass less than 100 GeV. The data from LEP improve this lower bound by 12 orders of magnitude, and require there to be a baryon-number or lepton-number violating coupling greater than 10^{-8} – 10^{-7} for squarks of mass less than 90 GeV. These lower limits can be significantly larger if there is large mixing in the squark sector or non-vanishing coupling to the Z boson.

The existence of R -parity-violating couplings means that a neutralino LSP will decay through a (possibly off-shell) squark to standard-model particles. A minimal R -parity-violating coupling of 10^{-20} , as allowed by exotic isotope searches, is not large enough to significantly reduce the number density of relic neutralinos. However, the data from LEP imply a lifetime of neutralinos that is 10^{24} times shorter, meaning that the neutralinos will have a negligible relic density. Hence, neutralinos cannot explain the excess of dark matter

in the Universe in the presence of squarks with mass less than 90 GeV.

When combined with upper limits on R -parity-violating couplings, our study leads to the conclusion that there may be very interesting signals of R -parity-violating supersymmetry at high energy colliders. In particular, squarks may be produced with lifetimes that are long enough to produce displaced vertices when they decay. In addition, R -parity-violation offers the possibility that superpartners may be produced singly, rather than in pairs, a subprocess that has significant advantages especially at collider energies that are not substantially higher than the masses of the produced states [12]. We urge additional attention in current and anticipated experiments to searches for explicit R -parity-violating decay modes.

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